A Virtual Reality System for Treatment of Phantom Limb Pain using Game Training and Motion Tracking

Bartal Henriksen
Aalborg University
School of Information and Communication Technology
Bhenri12@student.aau.dk

Ronni Nielsen
Aalborg University
School of Information and Communication Technology
Rnni07@student.aau.dk

Laszlo Szabo
Aalborg University
School of Information and Communication Technology
Lszabo09@student.aau.dk

Nicolaj Evers
Aalborg University
School of Information and Communication Technology
Nevers12@student.aau.dk

Martin Kraus
Aalborg University
Department of Architecture, Design, and Media Technology
Martin@create.aau.dk

Bo Geng
Aalborg University
Department of Health Science and Technology
BoGeng@hst.aau.dk

Abstract - **This paper describes the implementation of a phantom limb pain (PLP) home-based system using virtual reality (VR) and a motion sensor to immerse the users in a virtual environment (VE). The work is inspired by mirror therapy (MT), which has been used to relieve PLP. The target patient group focuses on unilateral upper-limb amputees with phantom pain. Using a motion sensor, the system tracks the movement of a user's hand and translates it onto the virtual hand. The system consists of exercises including opening and closing the hand, rotating the hand, and finer finger movements. These exercises are conveyed in the VR as three games: (1) A bending game, where the patients have to bend a rod, (2) a box game where the patients pick up and place boxes with their hands, (3) and a button memory game where the patients have to push buttons in a given sequence. These games were tested on twelve healthy participants to evaluate if the games encouraged similar movements as in MT. Prior to the experiment a preliminary test was conducted on an amputee with PLP to gather qualitative feedback from an end-user. The results indicated that the games did convey the exercises from the MT, although further testing is needed.**

Index Terms - **Virtual Reality; Virtual Environment; Phantom Limb Pain; Mirror Therapy**.

1. INTRODUCTION

With the appearance of widely accessible technical solutions, virtual reality (VR) is becoming an affordable daily reality for the general public. In particular, head-mounted displays are becoming consumer products; therefore, it is worthwhile to explore the possibilities of the technology for domestic purposes.

While software and hardware elements of VR are rapidly evolving, therapeutic uses of the technology are being conceptualized and realized as well. A therapeutic practice that could benefit from integrating into a virtual environment (VE) is the mirror therapy (MT) for phantom limb pain (PLP). A VR simulation could grant the therapy a more dynamic, immersive environment, which could greatly increase the potential and possibilities of its exercises, and provide the user a guided home treatment option. With the help of gameplay elements it could motivate the user to undergo the therapy on a regular basis.

In general 50%-85% of amputees experience PLP [2,3,4]. The pain is manifested most commonly as burning, tingling or cramping sensations [7]. A research of 2694 war veterans suffering from PLP showed average pain levels of 5.6 on the 11-point scale (10 being the worst possible pain and 0 no pain) during painful periods [8]. PLP is a serious condition that has an adverse effect on one's life quality. MT is a promising method of relieving PLP. While the underlying mechanism is not fully understood, it is considered to be a promising way of dealing with PLP and it does not include invasive operations or pharmaceutical treatment [5].

In MT a mirror is placed perpendicular to the body in front of the patient, so the patient can put the intact limb next to the mirror and see its reflection superimposed on the painful limb. The experience of receiving visual stimulus of having the amputated limb intact can be enough for restoring movement in a frozen phantom limb [6]. In the classical visuomotor version of the treatment, the participants are asked to do specific exercises with their intact and phantom limb synchronously, so the phantom hand moves along with the reflection in the mirror. A recent approach of the MT is the visuotactile MT. In this version the mirror is set up the same way, but instead of using movements, the amputee's stump is being mapped for relevant nerve endings and is receiving signals through tactile stimulation simultaneously [9]. The visuotactile approach widens the number of patients who can benefit from the MT as it has been proven useful in cases where the visuomotor approach was not successful [9]. The ultimate aim of the project is to create a therapeutic VR system capable of implementing both the visuomotor and visuotactile variations of the MT to maximize its therapeutic potential. To develop an introductory usability test it was decided to focus on the following therapeutic exercises: opening/closing the hand, wrist rotations and finer movements of the fingers.

2. METHOD

The system uses an Oculus Rift DK2 to visualize the VE and a Leap Motion sensor for tracking the hand movements. The Oculus Rift is a binocular head-mounted display developed by Oculus VR which uses stereopsis for creating an illusion of depth in a VE. The player is able to view virtual hands within the VR which move based on the input from the Leap Motion sensor. The Leap Motion is a motion sensor which detects hand and finger movement input. The Leap Motion sensor is placed on the table in front of the participant, captures the real hand and mirrors it into VR. Virtual versions of the hands are then displayed through the Oculus Rift.

2.1 VE setting and game setup

The VE consists of three games designed as training exercises promoting joint- and finer hand movement based on the specific training tasks: (1) The first game (bending game) includes opening and closing the fist as well as wrist rotations, (2) the second game (box game) promotes finer finger movements and (3) the third (button memory game) focuses on pushing buttons. Each game takes place in the same VE. The patient sits by the virtual table and is only able to interact with game objects placed on the virtual table. A virtual screen is placed on the back of the table and displays feedback of the progression within the games. The player is positioned by the virtual table in correlation to how they sit in front of the physical table. The Leap Motion is positioned so the virtual hands fit the position of the real hand.

2.1.1 Bending Game

This game incorporates the opening/closing hand and wrist rotation exercises. The bending game involves grabbing the handles on a rod and bending it in specific shapes to earn points. A screenshot of the game is shown in Figure 1 (left). The player has to move and rotate the rod into a predetermined area within the VE, displayed by a yellow transparent rod. Points will be earned based on how precise the player is placing the rod within the yellow transparent target. Both hands are shown in the VE, but only the intact hand controls them. The purpose is to have the player actively use the intact hand while imagining also using the phantom hand in synchronicity to match the visual information with the motor control.

2.1.2 Box Game

The box game focuses on exercises where the player has to use finer movements of the fingers. The goal of the game is to grab different colored cubes by pinching them, using the index finger and the thumb. The cubes must then be placed onto planes with the matching color in order to earn points. A screenshot of the game is shown in Figure 1 (middle). In this game, only a mirrored version of the intact hand is visualized within the VE and the player therefore has to coordinate the mirrored movements in order to complete the game.

2.1.3 Button Memory Game

The purpose of this game is to include a possible future implementation with a neurostimulator which facilitates tactile feedback. The game contains two groups of buttons floating above the table in front of the player. Each group contains six buttons positioned next to each other in a 3×2 matrix. A screenshot of the game is shown in Figure 1 (right). The game will activate a randomized sequence of buttons in one group and simultaneously mirror the sequence onto the other. The player must memorize and repeat this sequence by pressing the same sequence of buttons afterwards. The game visualizes both the intact and phantom hand in the scene, similar to the bending game.

2.2 Second Bending Game

A second iteration of the bending game was created. Instead of using the Leap Motion sensor for tracking the hand, a Perception Neuron motion capture glove was used. This allowed for more precise tracking while grabbing and releasing the rod, and enabled capturing a larger area for tracking. Furthermore, it was possible to track the movement of the whole arm, instead of only the hand. Besides the difference in hardware, there were also some changes in the game mechanics. A pair of submit buttons were implemented for the user to press after placing the rod inside the target to help visualize the transition to a new round and to encourage more grab/release movements. Colors and a sound system were added to further clarify the transition to a new round. Finally, a score system was added, visualizing points earned based on the position of the released rod and a timer to show the amount of time spent. A picture of the updated bending game can be seen in Figure 2.

3. EVALUATION

3.1 Preliminary test

Prior to the experiment, a preliminary test with an amputee was conducted to get feedback on the usability and what changes had to be made to the system in order for it to work as intended. Some changes were implemented based on the feedback from the participant, such as: displaying the Leap Motion sensor in the VE to prevent an issue with the player losing the position of the sensor in the real environment, making the virtual hand gradually transparent depending on its distance from the sensor, and changing the button memory game to make use of both hands to encourage the player to use both the intact-, and the phantom hand.

Figure 1. Screenshots of the three games. Left: Bending Game, middle: Box Game, right: Button Memory Game

3.2 Experiment

The experiment was designed as a within-subject test, where each participant experienced the three mentioned games. The order of the games was randomized to avoid carry over effects. The system was evaluated on 12 healthy participants (8 male, 4 female, age 21-29). The purpose of this experiment was to see if the games encouraged the participants to make the same hand exercises as described in Section 1. In order to evaluate whether or not the games did encourage the participants to do the exercises correctly, four main Likert items were assessed for each of the games. The Likert items were: “wrist:” “I was encouraged to use my wrist”, “index:” “I was encouraged to use my index finger”, “thumb:” “I was encouraged to use my thumb”, and “opening/closing:” “I was encouraged to open and close my hand”. Demographic data was also gathered, along with a usability questionnaire. The focus of the usability questionnaire was to find out how motivated the participants were when playing the games, and if the system had faults that could have potentially detrimental effect upon the experience.

3.2.1 Participants and Procedure

The experiment was conducted in a lab environment. When the participant arrived at the location, they were asked to sign a consent form, and then the experiment was explained. A demographic questionnaire was given to the participants that had to be filled out before they got to try the games. The participants were asked to sit down where the system was set up, and a training session was started, in order for the participants to get used to being in VR and using the Leap motion sensor. Then the first iteration started. After they tried the first iteration, a questionnaire was given, which involved questions about the game. This was done for all three games. After they were done with the three games, a final usability questionnaire was given.

3.3 Second Bending Game

The second bending game experiment was designed similar to the previous experiment and evaluated on 12 healthy participants. The test focused on evaluating whether the game encouraged the use of both hands and focusing on the usability; whether the game worked as intended and whether each system had faults that could potentially have detrimental effect upon the overall experience.

When the participant arrived at the location, they were asked to sign a consent form, and then the experiment was explained. This was followed by an initial phase where the motion capture glove was calibrated. Each participant then had a training phase to get used to using the head-mount display and the motion capture glove. The participant would then play the bending game for 14 rounds. After the game was completed, a questionnaire was given to the participants.

Figure 2. The second bending game

4. RESULTS

4.1 Evaluating the games

Figure 3 shows the three games and how the participants evaluated which of the four exercises were encouraged by the gameplay. The button memory game had a wide distribution across each Likert item and had a max value of 7 on every item. Regarding “index,” it primarily encouraged the use of the index finger, with only one outlier. The bending game had a large spread on “index” and “thumb” and as seen on “wrist” and “opening/closing” encouraged the use of wrist rotation and the opening and closing of the hand with one outlier in each. The box game had a low minimum value in “wrist,” “index” and “thumb,” but overall encouraged all four exercises with opening and closing the hand as the primary exercise, even with two outliers. Other than the four Likert items mentioned, the participants were given four open ended questions to each game. The open ended questions were: 1. “What parts of the game did you like?” 2. “What parts of the game did you dislike?” 3. “What problems did

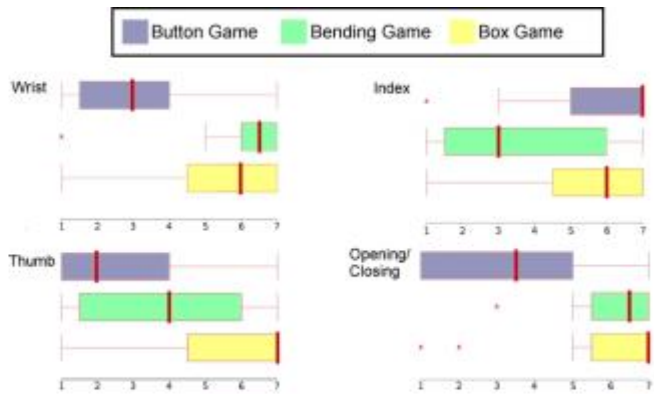

Figure 3. Responses for each of the four Likert items displayed as box- and whisker plots (described in Section 3) evaluating the exercises in the three presented games.

you run into?” 4. “What would you change?”

4.1.1 Bending Game

The bending game generally received positive feedback. Six participants noted that it was a simple task and it was easy to complete. It was also noted that it felt interactive and they were able to manipulate the tools in the environment. Five participants noted that the game was too difficult and three specifically noted the hand/wrist rotation was hard. Three participants noted they liked the challenge of the game and one specifically noted that it seemed like you actually used both hands: *“[...] it seems like I’m using both hands. I actually doubted which hand I was using in the real world, because I was looking at the right hand in the same (side), even though I used the left.”*

Four participants commented on the target position (the yellow cylinder). One felt it was hard to fit the rod in the correct angle. Three participants also commented they had trouble with releasing the rod when moving it into the target position. Two participants had comments on the screen with the score board, noting that it was “a bit off” and that it was distracting when completing the exercise. One further commented that the scoreboard should be completely removed.

4.1.2 Box Game

Five participants mentioned that they liked the mirroring of the hand. Four of the participants also noted that they found navigating the mirrored hand interesting and exciting. One participant further explained: “*[...] the mirroring went fine - I didn’t even notice it in the end.*” Two participants felt the assignment was simple. Three participants found the mirroring hand too hard to navigate. Though one participant liked the difficulty of the exercise, most of the other participants felt it was too hard. Eight participants commented on how the cubes were hard to grab and to release again. Two further commented that it was difficult to see if you were holding a box and two others noted that the physics of the cubes did not feel realistic. Three participants also noted that their hand disappeared at times within the game, especially when they had to stretch out to the corners of the game.

4.1.3 Button Memory Game

Generally the participants liked the game and found it easy to understand and to complete, although one participant felt they did not know when to proceed with the game and another found the game too easy. Two of the participants further explained they found the game fun. Another two also felt the movements of the hands felt realistic. Three participants noted they had trouble viewing the entire board of buttons and another three mentioned the buttons were too simple and felt they should be more interactive. Two participants noted that pressing the buttons was easy but another three noted that they sometimes pressed two buttons at once by accident or that the buttons did not recognize being pushed. One participant only used one hand to move both hands and explained: "*I only concentrated on the right side, as that was the hand I used, therefore it seemed quite easy*."

4.1.4 Functionality

The Likert item "*I knew the location of the Leap Motion sensor when wearing the Head-Mounted-Display*", which can be seen in Figure 4, has a median of 4 which shows that the location of the Leap Motion was not always immediately apparent to the user. The Likert item *"It was easy to move and select objects in the virtual environment"* was inconclusive as it had a median of 4 with a small variance of 1.3. *"I felt nauseous when using the system"* had a median of 1 with a low variance of 1.6, and no participants felt substantial motion sickness. Three Likert items examine the capabilities of the Leap Motion sensor: *"I had control over what I wanted to do"*, *"The functionality provided by the Leap Motion was sufficient to complete the tasks presented"* and *"The Leap Motion was easy to use"*. The participants overall were slightly positive towards the sensor, as every median value was larger than the neutral option ranging from 4.5 to 6 all with a variance ~2.

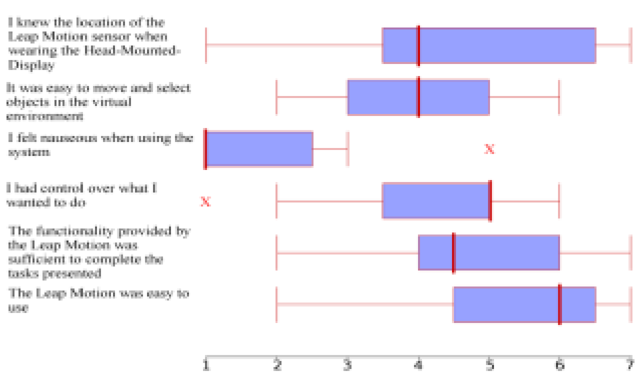

Figure 4. Each of the Likert items about the functionality of the system displayed as box- and whisker plots.

4.2 Second Bending Game

The following questions evaluated the game difficulty and visuals of the bending game layout (see Figure 5):

- (1) "*The task was easy to understand*"
- (2) "*I found the required task difficult*"
- (3) "*I quickly learned how to perform the required task*"
- (4) "*The task gradually increased in difficulty*"
- (5) "*I understood the user interface*"
- (6) "*It was clear when the game transitioned to the next game level*"
- (7) "*It was easy to understand how I was awarded points*"

Question (1) had a mean of 6.5, (2) had a mean of 2.58, (3) had a mean of 6.33 and (4) with a mean of 4.42. All participants found the task in the bending game easy to understand and felt they quickly learned how to perform the tasks. 9 out of 12 of the participants did not find the game difficult and only 5 noticed the game increasing in difficulty while 4 were uncertain if it did. The final score of the participants differentiated highly as it went from 113 to 207 with an average of 154. Furthermore, the time spent to complete the 14 rounds differentiated between 75 to 220 seconds with an average of 117. The Pearson's r correlation value indicates no clear connection between time spent and final score as the r-value between score and time is 0.1651. This could also indicate that even though the participants felt they understood the purpose of the game and how to perform the tasks it was unclear to them how well they performed the tasks and what they needed to do better in order to improve the score. One participant also indicated this by commenting "*[...] is was a bit unclear whether I continued to (the) next level without finishing this one or I should try again. It was a bit challenging to know whether I placed the rod correctly because it was always a bit sticking out*". Question (5) had a mean of 6.25 and (6) had a mean of 6.17, which indicates that participants felt they understood the interface and when the game transitioned onto the next level. The participants, however, did not seem to completely understand how they were rewarded points, as the answers for (7) spanned from 2: Disagree to 7: Agree with the mean being 4.75 and a spread of answers close to the median, indicated by the variance of 1.879. As all participants agreed they understood the interface it would further indicate the problem relies within how the points are added to the score.

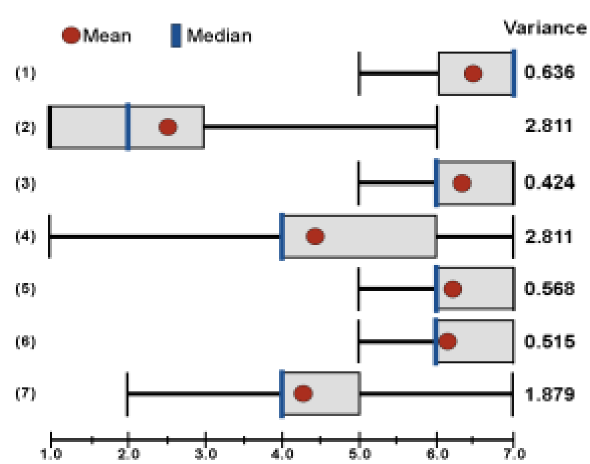

Figure 5. Second bending game responses (1-7)

The following questions evaluated the functionality and audiovisual feedback of the rod and the goal area within the bending game (see Figure 6):

- (8) "*It was easy to grab the rod*"
- (9) "*It was easy to let go of the rod*"
- (10) "*It was easy to place the rod within the goal*"
- (11) "*I was satisfied with the audiovisual feedback from the rod*"
- (12) "*I was satisfied with the audiovisual feedback from the goal*"
- (13) "*During the game it felt as if I was moving both my hands*"
- (14) "*The hand movement felt consistent with my real hand*"

Question (8) had a mean value of 5.67, (9) had a mean of 5.58 and (10) had a mean of 5.58. 10 out of 12 participants felt it was easy to grab and position the rod and 2 were uncertain. 10 further agreed that the rod was easy to let go while 2 disagreed. One participant noted that "*After pressing the buttons the hands automatically grabbed the handles (of the rod)*". This indicates that even though most participants felt it was easy to handle, the calibration should still be improved. Question (11) had a mean of 6.33 and (12) had a mean of 6.00. This indicates that the participants were satisfied with the audiovisual feedback provided by both the rod and the goal area. But as the purpose of the audiovisual goal feedback is to explain how well the rod is positioned, it would seem the feedback is not able to clarify this.

Question (13) had a mean of 4.75 and (14) had a mean of 5.58. Therefore the bending game did seem to encourage the majority of the participants to use both hands as only 3 out of 12 participants disagreed on this and the median was 5: slightly agree. Furthermore, the participants were generally positive in regards to whether the virtual hand movements were consistent with the real hand. The conductor further noted that four participants specifically moved both real hands while playing the bending game. It was also noted that the 3 of the 4 participants using both hands started the experiment with the bending game and the 4th played it in the second iteration. In general the participants did not seem to pay special attention to either hand, though a few participants occasionally viewed the mirrored hand.

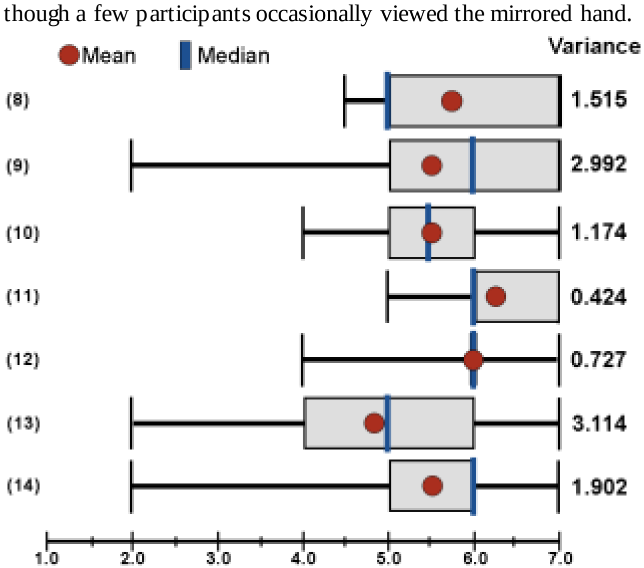

Figure 6. Second bending game responses (8-12)

5. DISCUSSION AND CONCLUSION

We developed an affordable VR system for treatment of PLP based on the MT. Using an Oculus Rift and a Leap Motion sensor, it was possible to correctly display a user's hand in a VE. The exercises based on MT were implemented into three VR games which included: a bending game, a box game, and a button memory game. The games were tested to see if they encourage the same hand movements as the ones based on the MT and to get results on the usability of the games. The results showed that in most cases the answers given were indicating that each game did encourage the intended exercise. Furthermore, it can be concluded that further improvements of each game must be implemented.

Bending Game: The bending game encouraged the intended hand movements. The participants were generally positive towards the game design and felt the game was interactive and straightforward; however, they did experience problems when releasing the rod into the targeted position. Many participants felt the movements were too difficult in general. Some participants further explained the scoreboard caused a distraction. While the hand movements for this game did work as intended, it is necessary to improve the game functionality as the experiment indicated it to be too difficult. In particular, releasing the rod was a problem. Furthermore, the scoreboard could be removed and more intuitive feedback could be implemented; e.g., changing the color of the target position as the player is improving, and implementing auditory feedback.

Box Game: The box game was generally successful in encouraging opening/closing of the hand and showed potential towards encouraging motions with the thumb and index finger. The feedback of the opening/closing element was overall positive, but also showed signs of major dissatisfaction. This is in line with the qualitative feedback that addresses the issue of having problems with getting the physical hand's opening/closing motion translated into the VE. The game received mixed, but overall positive reviews with regard to thumb and index finger activation. The low scored feedback can be explained with the tracking issue outlined with the hand opening/closing element as well, as the thumb/index finger activation and hand opening/closing is interconnected by design. Both positive and negative feedback stems from the same cause regarding the mirrored navigation of the single hand: some participants enjoyed the challenge while others found it overly difficult. This issue raises the need for a gameplay with increasing difficulty along the lines of flow theory [1].

Button Memory Game: The game did encourage the use of the index finger as intended. The participants were mostly positive about the experience, although some mentioned that it was difficult to see what the purpose of the game was. Another problem with the game was that some participants accidentally pressed two buttons at the same time, and sometimes a button was not activated when the participant pressed it. Although the general opinion was positive, there are many improvements to be made. The problem with two buttons being pressed accidentally can be resolved by having a wider space between the buttons. The issue with the game not showing what the purpose is can be resolved by providing visual and auditory feedback to the participants when a sequence is first given to them before they should interact with the buttons.

Second Bending Game: The second bending game was an updated version based on the feedback received from the experiment of the first bending game. The participants understood the task within the game and felt the rod was easy to grab, place and release within the goal area. However some grabbed the rod by accident which indicates the grab/release measurements could still be improved. The experiment further suggested the game was not difficult and it was unclear how points were awarded. This may have given the indication of the game being easy to complete, and the participants therefore did not focus on improving the placement of the rod before submitting. The game should therefore apply a better audiovisual feedback on how well the participants are doing, and the overall difficulty of the game should be revisited. The buttons also got overall positive feedback, although some interaction problems were noted. The participants seemed to hit the buttons multiple times by accident, as the buttons and the rod were placed too close to each other. One reason for the overall negative feedback of the buttons could be the positioning, and repositioning could improve it.

Comparison of Tracking Sensors: The Perception Neuron glove used in the second bending game provided a more stable and precise tracking, and has an unlimited tracking field, where as the leap motion is confined within the field of view of the camera inside it. Therefore, it was easier for the patients to play the second bending game, and made it easier for the patients to focus on the task at hand.

General Issues: The positioning of the physical Leap Motion sensor improved from the preliminary study; however, it was still not immediately apparent for the users. In a further iteration it is necessary to visualize the positioning, for example, by lighting the virtual Leap Motion sensor when the user is too far away. Visualizing barriers around the usable area might also be helpful. The participants generally felt that they had problems when interacting with the movable objects in the VE. In general, the game appeared too difficult for a new user. Furthermore, the participants were positive regarding the Leap Motion sensor although the results still indicated issues. Lastly, the most important future work is to have an experiment that compares this system with the MT. This will allow us to conclude if the system can be used as a supplement to the MT.

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